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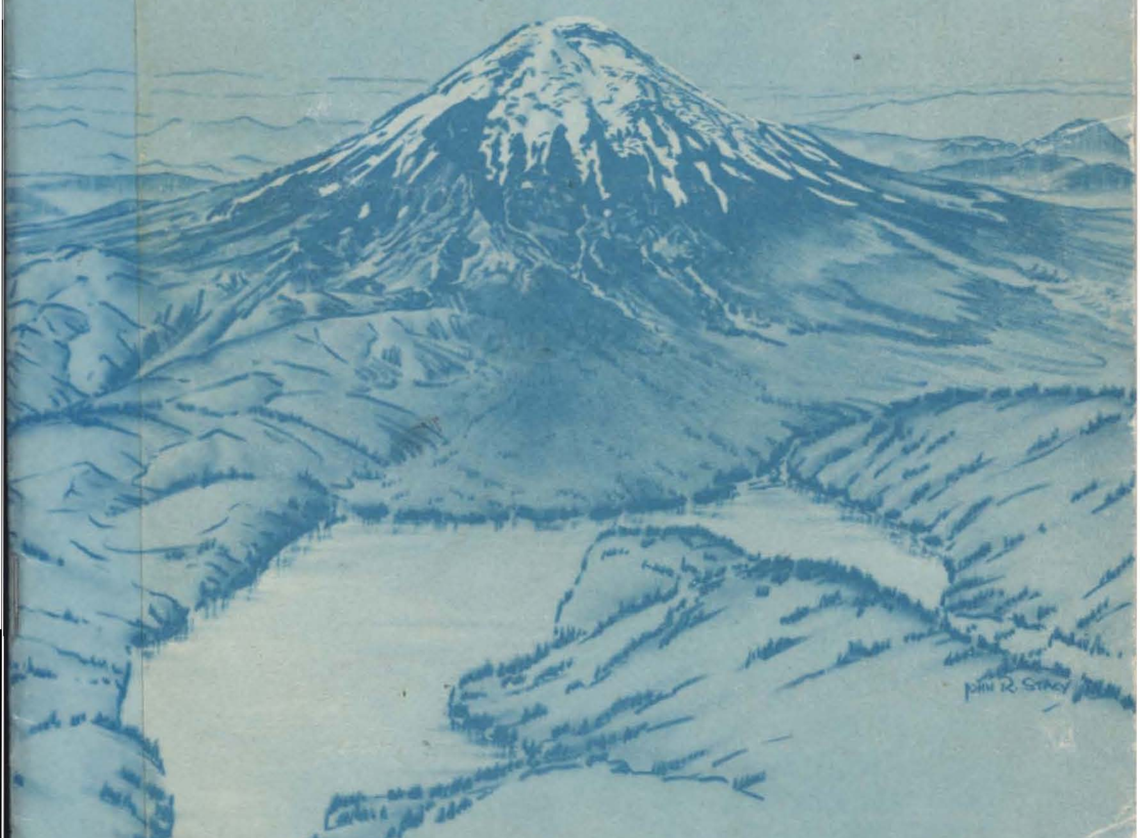
# POTENTIAL HAZARDS FROM FUTURE ERUPTIONS OF MOUNT ST. HELENS VOLCANO, WASHINGTON





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Aerial view of Mount St. Helens from the northeast.
Spirit Lake, in foreground, is dammed by a broad fan of mudflow deposits that was formed during a major eruptive period between 800 and 1200 B.C. Copyrighted photograph courtesy Delano Photographics.

# Potential Hazards from Future Eruptions of Mount St. Helens Volcano, Washington

*By* DWIGHT R. CRANDELL *and* DONAL R. MULLINEAUX

GEOLOGY OF MOUNT ST. HELENS VOLCANO, WASHINGTON

GEOLOGICAL SURVEY BULLETIN 1383-C

*An assessment of expectable kinds of future eruptions and their possible effects on human life and property*

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1978

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

H. William Menard, *Director*

First Printing 1978
Second Printing 1980
Third Printing 1980

Library of Congress Cataloging in Publication Data
Crandell, Dwight Raymond, 1923-
Potential hazards from future eruptions of Mount St. Helens Volcano, Washington.
(Geology of Mount St. Helens Volcano, Washington)
(Geological Survey Bulletin 1383-C)
Bibliography: p. 25
Supt. of Docs. no.: I 19.3:1383-C
1. Saint Helens, Mount, Wash. 2. Natural disaster–Washington (State)–Saint Helens, Mount.
I. Mullineaux, Donal Ray, 1925- joint author.
II. Title. III. Series. IV. Series: United States Geological Survey Bulletin 1383-C.
QE75.B9 no. 1383-C [QE523.S23] 557.3'08s [551.2'1] 77-608134

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

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## METRIC EQUIVALENTS

| *Metric measure* | | *Approximate equivalent* |
|---|---|---|
| 1 centimeter (cm) | = | 0.4 inch |
| 1 meter (m) | = | 3.3 feet |
| 1 kilometer (km) | = | 0.6 mile |
| 1 cubic meter ($m^3$) | = | 1.3 cubic yards |
| 1 square kilometer ($km^2$) | = | 0.4 square mile |
| 1 cubic kilometer ($km^3$) | = | 0.24 cubic mile |

# POTENTIAL HAZARDS FROM FUTURE ERUPTIONS OF MOUNT ST. HELENS, VOLCANO, WASHINGTON

By DWIGHT R. CRANDELL and DONAL R. MULLINEAUX

ABSTRACT

Mount St. Helens has been more active and more explosive during the last 4,500 years than any other volcano in the conterminous United States. Eruptions of that period repeatedly formed domes, large volumes of pumice, hot pyroclastic flows, and, during the last 2,500 years, lava flows. Some of this activity resulted in mudflows that extended tens of kilometers down the floors of valleys that head at the volcano. This report describes the nature of these phenomena and their threat to people and property; the accompanying maps show areas likely to be affected by future eruptions of Mount St. Helens. Explosive eruptions that produce large volumes of pumice affect large areas because winds can carry the lightweight material hundreds of kilometers from the volcano. Because of prevailing winds, the 180° sector east of the volcano will be affected most often and most severely by future eruptions of this kind. However, the pumice from any one eruption probably will fall in only a small part of that sector. Pyroclastic flows and mudflows also can affect areas far from the volcano, but the areas they affect are smaller because they follow valleys. Mudflows and possibly pyroclastic flows moving rapidly down Swift and Pine Creeks could displace water in Swift Reservoir, which could cause disastrous floods farther downvalley.

## INTRODUCTION

Mount St. Helens is a symmetrical volcanic cone in southwestern Washington about 75 km northeast of Portland, Oreg. (fig. 1). Most of the visible part of the cone has been formed within the last thousand years, but it overlies an older volcanic center that evidently came into existence before 36,000 years ago (Hyde, 1975, p. B10). Mount St. Helens has had a long history of spasmodic explosive activity, and we believe it to be an especially dangerous volcano because of its past behavior and the relatively high frequency of its eruptions during the last 4,500 years (table 1). In the future,

Mount St. Helens probably will erupt violently and intermittently just as it has in the recent geologic past, and these future eruptions will affect human life and health, property, agriculture, and general economic welfare over a broad area.

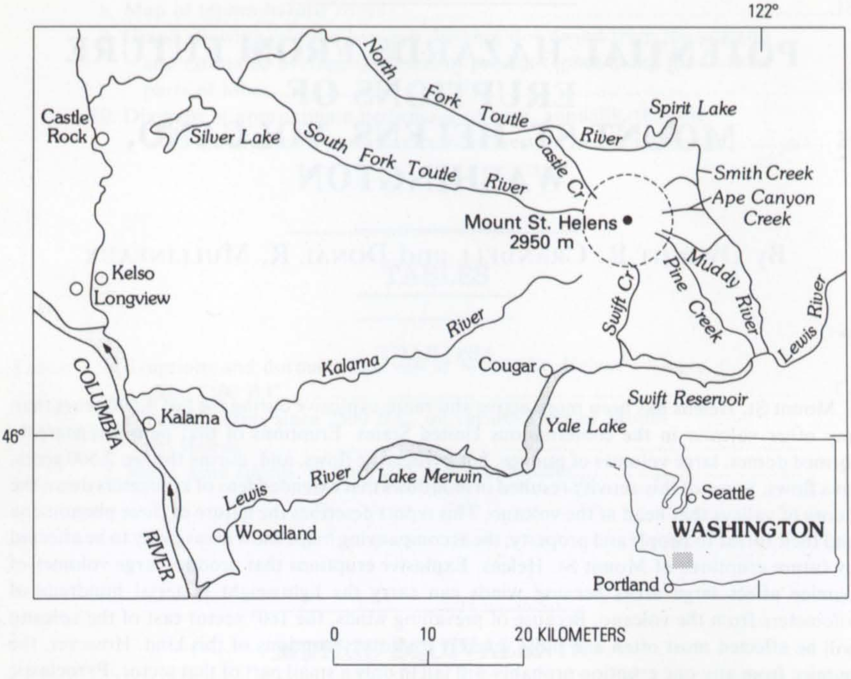


FIGURE 1.—Index map of the Mount St. Helens region. Dotted circle indicates a generalized outline of the base of the volcano.

A forecast in this report of the frequency and possible effects of future volcanism is based on the assumption that eruptions will be roughly of the same frequency, kinds, and scale as those which occurred repeatedly during the last 4,500 years. That period included a variety of eruptive events (table 2). Large areas were affected adjacent to and downvalley from the volcano (pl. 1) as well as downwind from it (fig. 2).

Streams that head on the volcano enter three main river systems: the Toutle River on the north and northwest, the Kalama on the west, and the Lewis River on the south and east (fig. 1). The Lewis River is impounded by three dams for the purpose of hydroelectric power generation; the south and east sides of the volcano drain into Swift Reservoir directly south of the volcano. All three reservoirs on the Lewis River are used extensively for recreation, as is Spirit Lake, which is impounded in the North Fork Toutle River valley by a natural dam formed chiefly of mudflow deposits (frontispiece).

TABLE 1—*Eruptions and dormant intervals at Mount St. Helens since 2500 B.C. (Crandell and others, 1975)*

[The circles represent specific eruptions that were observed or that have been dated or closely bracketed by radiocarbon age determinations; the vertical boxes represent dormant intervals]

| | |
|---|---|
| A.D. 1900 | Dormant interval of 120 years |
| | Dome and tephra eruptions, lava flows (?) |
| 1800 | Tephra eruption, mudflows |
| | Apparent dormant interval of ca. 150 years |
| 1700 | |
| | Pyroclastic flows |
| | Dome eruption, mudflows |
| 1600 | |
| | Apparent dormant interval of ca. 100 years |
| 1500 | Tephra eruptions, pyroclastic flows |
| 1400 | Pyroclastic flows |
| SCALE CHANGE 1300 | |
| 1200 | |
| 1100 | Apparent dormant interval of 400–500 years |
| 1000 | |
| 900 | |
| | Tephra eruption |
| 800 | |
| 700 | |
| | Apparent dormant interval of 400–500 years |
| 600 | |
| 500 | |
| 400 | |
| | Tephra eruptions, mudflows |
| 300 | |
| 200 | Tephra eruptions |
| A.D. 100 | Lava flows |
| 0 | |
| | Pyroclastic flows, mudflows |
| B.C. 100 | |
| | Pyroclastic flows |
| 200 | |
| | Pyroclastic flows, tephra eruptions, mudflows |
| 300 | Tephra eruptions, mudflows |
| | Lava flows |
| 400 | |
| SCALE CHANGE | Apparent dormant interval of 400–500 years |
| 500 | |
| | Repeated eruption of large pyroclastic flows, domes, and tephra; mudflows |
| 1000 | |
| 1500 | Apparent dormant interval of ca. 400 years |
| | Intermittent tephra eruptions of large volume, pyroclastic flows, eruptions of domes; mudflows |
| 2000 | |
| B.C. 2500 | |
| | Apparent dormant interval of 4000 years |

TABLE 2.—*Volcanic events and deposits formed since*

[Unless specified, distances given are measured from base of volcano, which is close to 4,400-ft contour on the northeast side and 4,000-ft contour elsewhere. Symbol ≥ indicates as far as or farther than distance specified. Asterisk (*) indicates age not known

| Time scale | Tephra erupted at Mount St. Helens: Set designation[1] | Tephra erupted at Mount St. Helens: Description | North and northwest sides: Valleys of Castle Creek and North Fork Toutle River |
|---|---|---|---|
| A.D. 1900 | | | **Mudflows** reached ≥3 km. |
| 1800 | T | **Pumice**; single layer, light gray; contains hy, hb, ag.[2] As thick as 50 cm, mostly lapilli.[3] Extends NE. of volcano. | **Dacite dome** (Goat Rocks) erupted on flank of cone, rock falls, avalanches, and mudflows of hot debris moved downslope from dome; andesite lava flows on flank of volcano. |
| 1700 | | | |
| 1600 | | | **Pyroclastic flow** reached ≥5 km. **Mudflows of debris** from summit dome moved ≥9 km. |
| 1500 SCALE CHANGE | W | **Pumice**; many layers, light gray; contains hy, hb.[2] As thick as 150 cm, lapilli and bombs.[3] Occurs on N., E., and S. flanks of volcano; extends far beyond volcano to NE. (layer Wn) and to E. (layer We). | **Andesite lava flows** moved ≥3 km. **Hot mudflow** reached ≥3 km.[4] **Mudflows** extended to Spirit Lake. |
| 1000 | | | **Strong laterally directed explosion** threw rock debris from side of dome (Sugarbowl) NE. to distance of ≥6 km. |
| 500 | | | |
| A.D. 0 B.C. | B | **Scoria**; several layers, brown; contains hy, ag, ol.[2] As thick as 30 cm, ash and small lapilli.[3] Occurs on all flanks of volcano; extends beyond volcano to N., E., and S. | **Pyroclastic flow** on flank of cone **Lava flow** on flank of cone **Pyroclastic flows** reached ≥4 km. **Andesite lava flow** extended ≥5 km. |
| 500 | ? | | |
| 1000 | P | **Pumice**; several layers, yellowish gray; contains hy, hb.[2] As thick as 70 cm, ash and lapilli.[3] Occurs on all flanks of volcano; extends beyond volcano chiefly to N. and E. | **Pyroclastic flows and mudflows** extended to Spirit Lake and into North Fork Toutle River valley; several mudflows moved ≥70 km downvalley to site of Castle Rock.[5] |
| 1500 | ? | | |
| 2000 | Ye Yn Y | **Pumice**; several layers, grayish yellow; contains cm, hb.[2] Probably 100–200 cm thick; lapilli and bombs. Occurs on all flanks of volcano; extends far beyond volcano to NE. (layer Yb), NNE. (layer Yn), and E. (layer Ye) | |
| B.C. 2500 | Yb | | **Pyroclastic flows and mudflows** extended into North Fork Toutle River valley; mudflows reached ≥30 km downvalley. |

[1]The tephra sets and layers are described by Crandell and Mullineaux (1973) and by Mullineaux, Hyde, and Rubin (1975).

[2]Heavy minerals contained in tephra deposits: hy, hypersthene; hb, hornblende; ag, augite; cm, cummingtonite; ol, olivine.

[3]At distance of 10 km from summit of volcano in direction of thickest part of deposit.

[4]A radiocarbon date of 460±200 years (U.S. Geological Survey sample W-2824) was obtained on charcoal from this

The community nearest the volcano is Cougar, which is in the Lewis River valley about 18 km to the south-southwest. The principal resource of the region is timber, and many areas adjacent to the volcano either have been logged recently or are now being logged.

## PRODUCTS OF ERUPTIONS AND ASSOCIATED HAZARDS

Future eruptions probably will produce lava flows, domes, tephra (pumice and other airborne rock debris), and pyroclastic flows, most of

*2500 B.C. on various sides of Mount St. Helens*

except within rather wide limits. Radiocarbon dates on which ages of deposits and events in this table are based have been "corrected" by use of Suess' (1970) tree-ring calibration curves]

| East and southeast sides<br>Valleys of Smith, Ape Canyon, and Pine Creeks and Muddy River | South and southwest sides<br>Valleys of Swift Creek and Kalama River | Time scale |
|---|---|---|
| **Mudflows** on flank of cone. | | A.D.<br>1900 |
| | **Lava flows** on flank of cone. | |
| | | 1800 |
| **Mudflows of rock debris** from summit dome moved ≥9 km. | **Mudflows** of rock debris from summit dome. | 1700 |
| | | 1600 |
| | **Pyroclastic flows.** | |
| **Andesite lava flows** on flank of cone.* | **Andesite lava flows** on flank of cone.* | 1500 |
| | **At least 3 pyroclastic flows** moved 9 km down Kalama River valley; 2 or more mudflows and a pyroclastic flow reached ≥4 km down Swift Creek valley. | SCALE CHANGE<br>1000 |
| **Formation of dacite dome** ("east-side dome").* | | |
| | | 500 |
| | **Basalt lava flows** moved 12 km down both valleys. | A.D.<br>0<br>B.C. |
| **Pyroclastic flow** moved ≥3.5 km down Ape Canyon. | **Pyroclastic flow** in Swift Creek valley. | |
| **Lava flows** on flank of cone; **mudflows** reached ≥10 km in Pine Creek valley. | **Six or more mudflows** in Swift Creek valley. | |
| **Andesite lava flow** moved ≥5 km down Muddy River valley.* | **One or more mudflows** extended ≥30 km down valleys of Swift Creek and Lewis River. | 500 |
| **Eight or more pyroclastic flows and many mudflows** moved down Pine Creek valley; some pyroclastic flows extended ≥13 km; some mudflows moved ≥18 km. | **Pyroclastic flows. Mudflows** extended ≥8 km down Swift Creek valley and ≥45 km down Kalama River valley. | 1000 |
| | **Formation of dacite dome.*** | |
| | **Pyroclastic flow** on west flank of cone. | |
| | | 1500 |
| **Pyroclastic flows** moved ≥11 km, **mudflows** ≥15 km down Pine Creek valley. | | |
| | | 2000 |
| **Pyroclastic flows and mudflows** extended ≥4 km down valleys of Smith and Ape Canyon Creeks. | | B.C.<br>2500 |

mudflow. The "corrected" date suggests that the deposit was formed about A.D. 1420. However, the mudflow evidently is younger than tephra set W, which was erupted about A.D. 1500.

[5]A radiocarbon date of 2,030±240 years (sample W-811) ("corrected" date about 100 B.C.) was obtained on wood from lowest mudflow of sequence exposed near Gilmore Corners, Wash. (Mullineaux and Crandell, 1962). Stratigraphic relations closer to the volcano suggest that the mudflow sequence was formed, as shown here, between 1200 and 700 B.C.

which will be accompanied by the emission of gases; some of these eruptions may cause mudflows to be formed. These potentially dangerous events are explained and discussed in the following text, and their anticipated geographic extents are shown on plate 2 and in figure 7.

The nature of future eruptions, and of the resulting kinds of rocks, will depend largely on the kind or kinds of magma that move into the volcano. Eruptions in the past have been of three main kinds of magma, which have produced rocks known as basalt, andesite, and dacite. These rocks differ in their chemical composition, and especially in the percentage of silicon

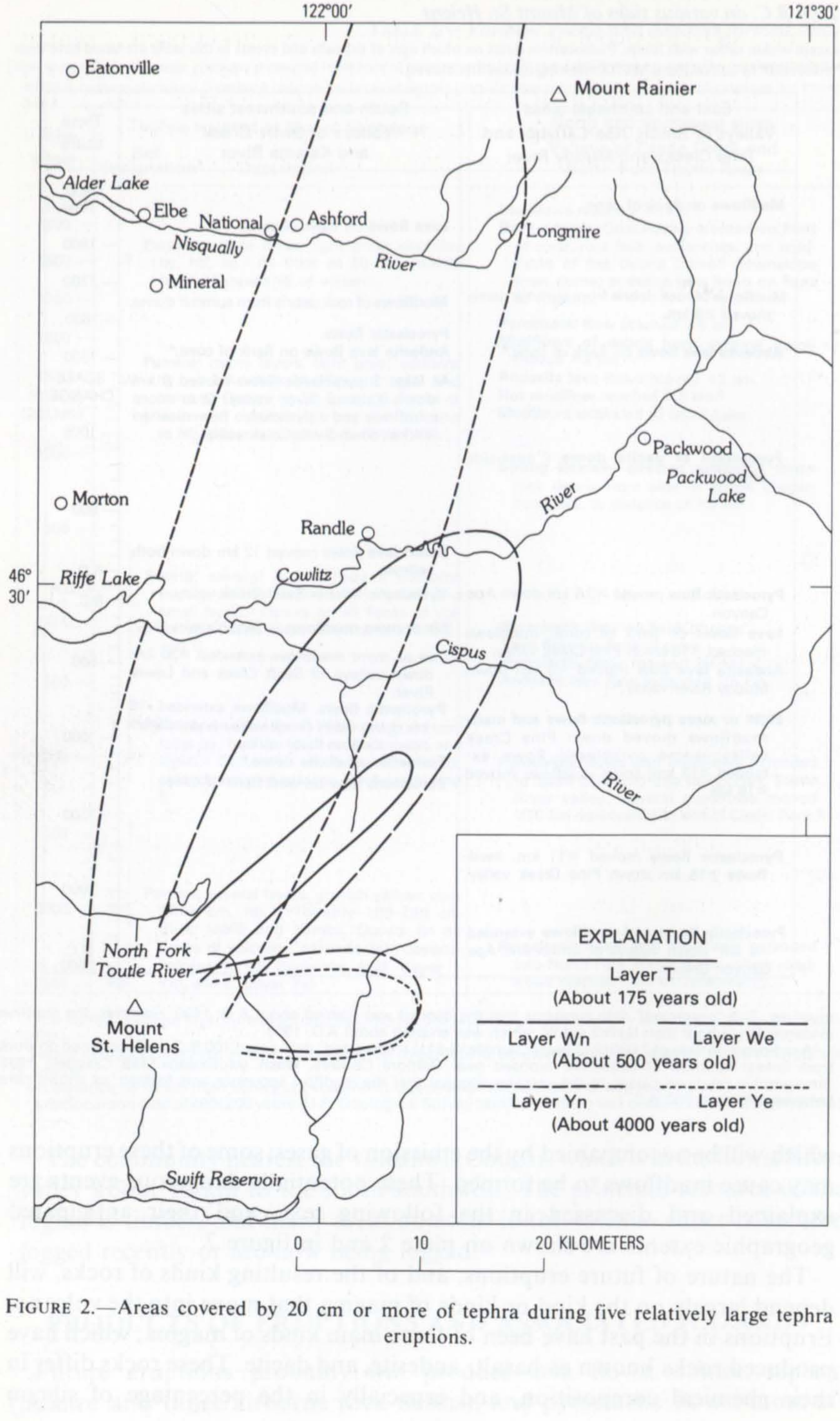


FIGURE 2.—Areas covered by 20 cm or more of tephra during five relatively large tephra eruptions.

dioxide ($SiO_2$) they contain. The $SiO_2$ content of basalts erupted at Mount St. Helens ranges from 50 to 55 percent, of andesites 56 to 62 percent, and of dacites 63 to 68 percent (C. A. Hopson, written commun., 1972). The chemical composition of magma determines in large part the ways in which it will be erupted. In general, basalt magma like that erupted at Mount St. Helens is relatively fluid and tends to be erupted quietly to form lava flows. Highly explosive eruptions are uncommon because gas escapes relatively readily from such a magma. At Mount St. Helens, explosive eruptions of basalt tephra have been uncommon and of small volume. Dacite magma is relatively viscous and gases do not readily escape from it. The initial eruption of gas-rich dacite commonly is explosive and forms pumice; domes are often formed at or near the end of the eruption. Eruptions of andesite magma typically are intermediate in behavior between basalt and dacite. Some andesitic eruptions at Mount St. Helens have been explosive and have formed tephra; others have formed only lava flows.

### LAVA FLOWS

The quiet eruption of hot, relatively fluid molten rock (lava) forms lava flows; flows move downslope away from their source vents until the lava cools and solidifies (fig. 3). Typically, lava from volcanoes like Mount St. Helens appears only after an eruption has been in progress for days or weeks, rather than during the first part of the eruption.

Future flows at Mount St. Helens like those of the recent past probably will be erupted from vents on the flanks of the volcano, because the large dome that forms the summit is likely to divert rising magma to the volcano's flanks (fig. 4). Flank eruptions will affect only the areas that are downslope from vents, and the paths of flows can thus be anticipated shortly after an eruption begins. Based on the extent of most previous lava flows at Mount St. Helens, future flows probably will not extend more than about 5 km beyond the base of the volcano and few will reach beyond the volcano's flanks.

Motion pictures of lava moving at a high speed have given rise to the common misconception that lava flows move forward so rapidly that people cannot escape; however, lava rarely moves rapidly unless it is flowing down a steep slope along a well-established channel. The fronts of lava flows usually advance at rates ranging from those which are barely perceptible to about as fast as a person can walk.

Although lava flows present relatively little direct danger to human life, those that extend into and melt deep snow could cause destructive floods and mudflows. Elsewhere, lava moving into a forest could start fires.

### DOMES

Volcanic domes are masses of solid rock that are formed when stiff, pasty lava erupted from a volcanic vent is so viscous that it extends as far upward as outward, and forms a mushroom-shaped cap over the vent (fig. 4). A lava

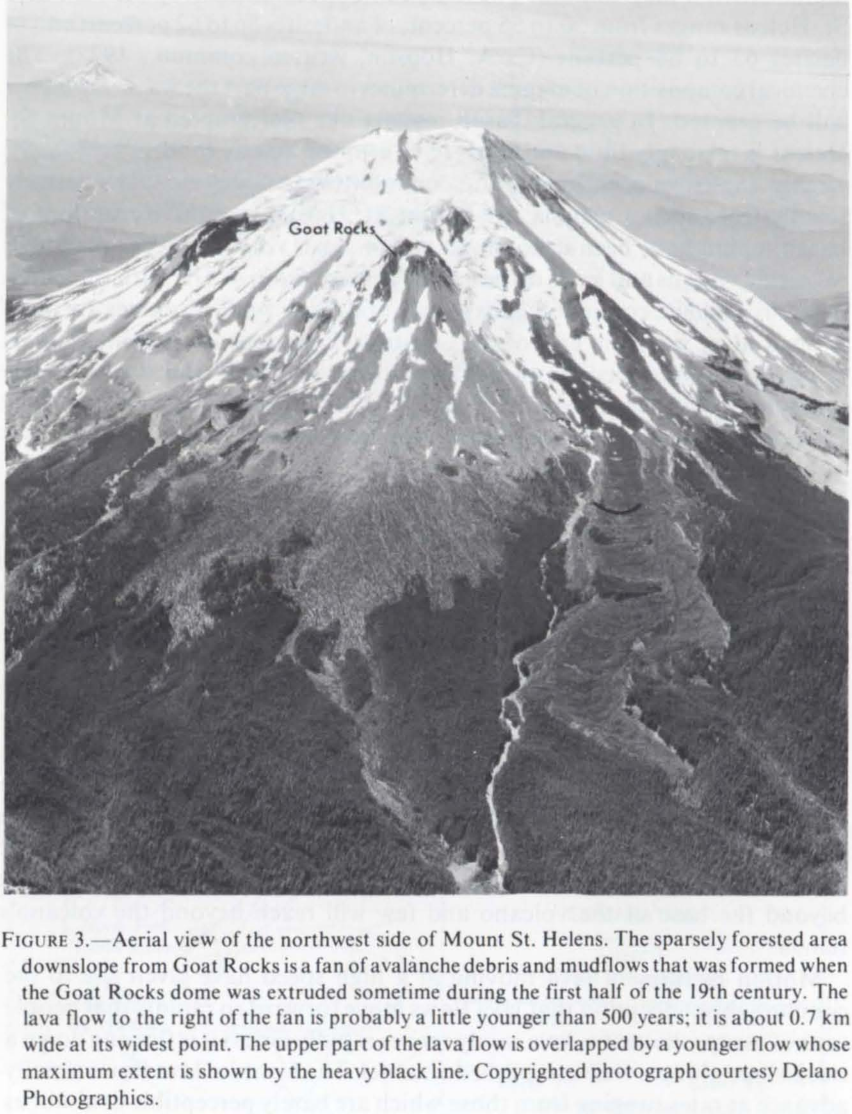


FIGURE 3.—Aerial view of the northwest side of Mount St. Helens. The sparsely forested area downslope from Goat Rocks is a fan of avalanche debris and mudflows that was formed when the Goat Rocks dome was extruded sometime during the first half of the 19th century. The lava flow to the right of the fan is probably a little younger than 500 years; it is about 0.7 km wide at its widest point. The upper part of the lava flow is overlapped by a younger flow whose maximum extent is shown by the heavy black line. Copyrighted photograph courtesy Delano Photographics.

flow will result if the molten rock is fluid enough to move sideways from the vent over the surface of the ground, and gradations exist between lava flows and domes. The sides of domes are typically steep and very unstable and commonly collapse during or shortly after formation. Domes may also be partly destroyed by explosions.

Domes, like lava flows, usually are formed after other kinds of activity have occurred and are generally erupted even more slowly than lava flows. Because of the presence of the summit dome (fig. 4) most future domes at Mount St. Helens probably will be erupted from vents on the flanks of the

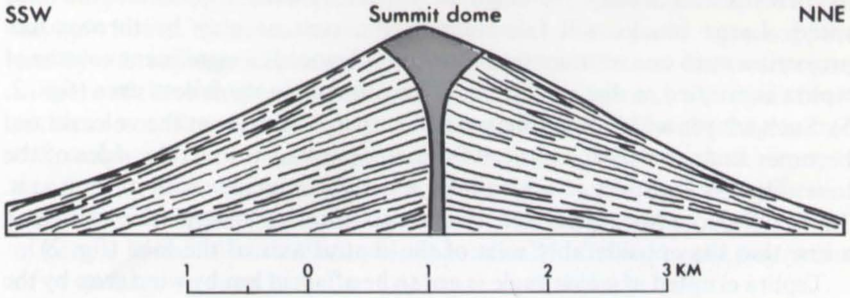


FIGURE 4.—Diagrammatic cross section through Mount St. Helens volcano showing inferred relation of summit dome to lava flows and interbedded rubbles, which are schematically represented by the line pattern. The base of the cross section is at an altitude of about 1,225 m. No vertical exaggeration.

volcano, like the Goat Rocks dome (fig. 3). The direct effects of a dome eruption would be confined to nearby areas; they would include destruction of the preexisting surface, burial of closely adjacent areas by rock debris, and possibly forest fires started by hot rock fragments.

A greater danger, however, exists from the associated indirect effects. For example, explosions can cause large rockfalls from the flanks of domes, and these, in turn, may become swiftly moving avalanches of rock debris. Explosions can also cause lateral blasts of great force which can carry steam and rock fragments from the dome outward at a high speed to distances of at least 10 km. Pyroclastic flows, rock-debris avalanches, and mudflows associated with the dome eruption could affect areas much farther away.

## TEPHRA

Tephra is the term used in this report to describe particles of molten or solid rock of any size that are erupted into the air above a volcano. Eruptions that produce tephra may range from explosively rapid, continuous rushes of fragment-laden gas that continue for hours, to blasts that last only a few seconds. Most explosions are directed upward at high angles, but some are directed laterally at low angles. The eruptions that produce tephra grade into those that form pyroclastic flows; some definitions of tephra even include the deposits of pyroclastic flows (Thorarinsson, 1974), but the term is used in a more restricted sense, for airfall deposits only, in this report.

A tephra eruption can occur suddenly and be the first or one of the first events of an eruptive episode. Very large volumes of tephra generally are not produced at the outset of an eruption, but may be ejected within a few hours or a few days.

Individual tephra fragments may consist of solid rock or may be pumice in which innumerable cavities were formed by gas bubbles trapped in the molten material as it cooled and solidified. Tephra particles usually are projected high above the volcano; winds carry them away from the volcano until they ultimately fall back to the ground surface at a distance determined

by their size and density, the height to which they were erupted, and the wind speed. Large blocks will fall close to the vent or may be thrown like projectiles onto one or more flanks of the volcano. If a significant volume of tephra is erupted, a distinct layer will accumulate in the fallout area (figs. 2, 5). Such a layer will form a lobate blanket that is thickest at the volcano and becomes thinner with increasing distance as well as toward the sides of the lobe. The thickest part of such a lobe generally coincides with its long axis. Tephra Yn, from Mount St. Helens is an exception because it is thickest along a line that lies considerably west of the central axis of the lobe (fig. 2).

Tephra erupted at a low angle is apt to be affected less by wind than by the direction of the blast. Deposits of most lateral blasts are thin but may include large blocks of solid rock. Such blasts often are associated with the formation of a volcanic dome, and they generally affect only the side of the volcano on which the dome is being erupted.

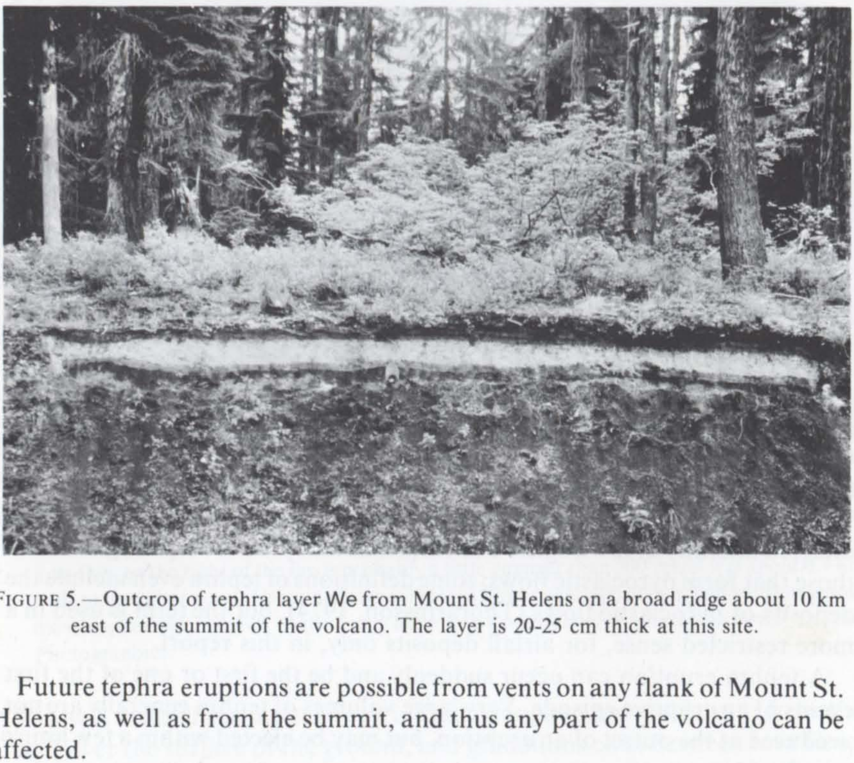

FIGURE 5.—Outcrop of tephra layer We from Mount St. Helens on a broad ridge about 10 km east of the summit of the volcano. The layer is 20-25 cm thick at this site.

Future tephra eruptions are possible from vents on any flank of Mount St. Helens, as well as from the summit, and thus any part of the volcano can be affected.

Tephra endangers lives and property by the impact of flying fragments, by forming a blanket covering the ground surface, by producing a suspension of fine particles in air and water, by carrying acids, and, close to the vent, by its heat. People can be injured by falling fragments, by breathing tephra-contaminated air, by collapse of tephra-laden roofs, and by fires started by hot fragments. Tephra eruptions can also result in psychological stresses by

blocking roads and causing people to be isolated, by causing darkness during daylight hours, by increasing acidity and turbidity in exposed water supplies, and by interrupting telephone, radio, and electrical services. Exposure to one or more of these stresses may lead to panic even though an individual's health or life is not directly endangered. Damage to property results largely from the weight of tephra, especially if it becomes water soaked, from its smothering effect, from abrasion, and from corrosion. Machinery is especially susceptible to the last two effects. The health and economic welfare of people in the fallout area can also be radically affected by the destruction of or damage to food crops and domesticated animals.

Hazards from tephra decrease rapidly in severity downwind, so that beyond a distance of 25-30 km tephra from most eruptions is more likely to cause maintenance and clean-up problems than to present a direct hazard to human life. However, even small amounts of tephra falling for a period of weeks or months can have serious cumulative effects on health and economic welfare.

### VOLCANIC GASES

Volcanoes emit gases, sometimes alone, sometimes in conjunction with the eruption of molten or solid rock materials. Gases erupted under great pressure generally carry some rock material, but quiet emission of gas alone is common. Gases emitted by volcanoes consist chiefly of water vapor, carbon dioxide, carbon monoxide, and various compounds of sulfur, chlorine, and nitrogen; some volcanoes also emit fluorine. Many eruptions begin and end with gas emission, but discharge of gases does not necessarily signify that an eruption is about to begin, nor does it invariably occur before an eruption.

Quietly emitted gases may be concentrated and "strong" near a vent, but usually disperse rapidly and become diluted downwind. Distribution of the gases is mostly controlled by wind, and dilute gas odors have been reported many tens of kilometers downwind from erupting vents. Explosively erupted gases may be driven laterally away from a vent at high speed, but they quickly lose force, and then drift and disperse.

Volcanic gases can be dangerous to health or life as well as to property (Wilcox, 1959, p. 442-444). Gases are potentially injurious to people mainly because of the effects of acid and ammonia compounds on eyes and respiratory systems, and they may also have other adverse effects. Enough carbon dioxide and carbon monoxide can collect in local basins to suffocate unwary animals or people. Gases can harm plants and can poison animals that eat the plants; they also can corrode metal. Cumulative effects of dilute volcanic gases over a long period may cause substantial property damage.

### PYROCLASTIC FLOWS

Pyroclastic flows are masses of hot, dry rock debris that move like a fluid but that owe their mobility to hot air and other gases mixed with the rock debris. They consist of a coarse basal flow and an accompanying hot dust

cloud (fig. 6). Pyroclastic flows can form when large masses of hot rock fragments are suddenly erupted onto the volcano's flanks or when a side of a growing volcanic dome topples or slides outward and downward and shatters into countless fragments of hot rock.

These masses of hot rock debris can move downslope at high speed owing to the force of gravity, to the force of the eruption, or to both. Under favorable conditions they can travel at speeds of 50 to more than 150 kilometers per hour (km/h). The velocity of pyroclastic flows seems to depend mostly on their volume, and on the slope of the surface over which they move.

The coarse basal parts of pyroclastic flows move along the ground surface and the clouds of hot dust that accompany them may blanket adjacent areas, especially those downwind from the flows. Although pyroclastic flows may spread out if they reach flat areas, because of their density they generally move like water into low areas and are mostly confined to valley floors.

Because of their great mobility, pyroclastic flows can affect areas at considerable distances from the volcano. On the basis of past events at Mount St. Helens, nearly all areas within a distance of 6 km from the base of the volcano could be affected by basal parts of future pyroclastic flows or their accompanying ash clouds; valley floors could be affected for an additional distance of at least 10 km.

The principal dangers from pyroclastic flows result from (1) the basal flow of hot, relatively coarse rock debris which can bury and incinerate people and objects in its path, and (2) the cloud of hot ash and gases which may accompany the basal flow or occur alone. Such clouds may cause asphyxiation, burning of the lungs by hot dust or steam and other gases, and burning of the skin. In addition, rock fragments carried in the clouds may cause injury by impact, and both impact and heat can damage property.

The especially severe hazard to human life represented by a pyroclastic flow is due to its great speed and its high temperature. Clouds of hot ash associated with pyroclastic flows that were formed during the 1951 eruption of Mount Lamington, Papua, were hot enough to char wood. One such cloud was estimated to have maintained a temperature of 200° Celsius (C) for a period of 1.5 minutes as it passed a site about 9 km from the volcano (Taylor, 1958). Hot pyroclastic flows produced during that eruption killed 3,000 persons. The cloud from Mount Pelée volcano that devastated St. Pierre, Martinique, in 1902 and killed nearly 30,000 persons is estimated to have had a velocity of at least 160 km/h and a temperature of 700°-1,000°C (Macdonald, 1972, p. 144-146).

## MUDFLOWS

A mudflow is a mass of water-saturated rock debris, typically containing a wide variety of particle sizes (fig. 7), that moves downslope as a fluid under the influence of gravity. During movement, mudflows resemble flowing masses of wet concrete, and because of their fluid nature they generally

FIGURE 6.—Photograph of a hot pyroclastic flow descending a valley on the north slope of Mount Pelée in Martinique. The basal, coarse part of the flow is obscured by clouds of ash that rise hundreds of meters above it. Photograph by A. Lacroix, December 16, 1902. Published with permission of Masson, S. A., Paris.

follow channels and valleys. The rock debris in many volcanic mudflows is derived from masses of loose, unstable material that result from explosive

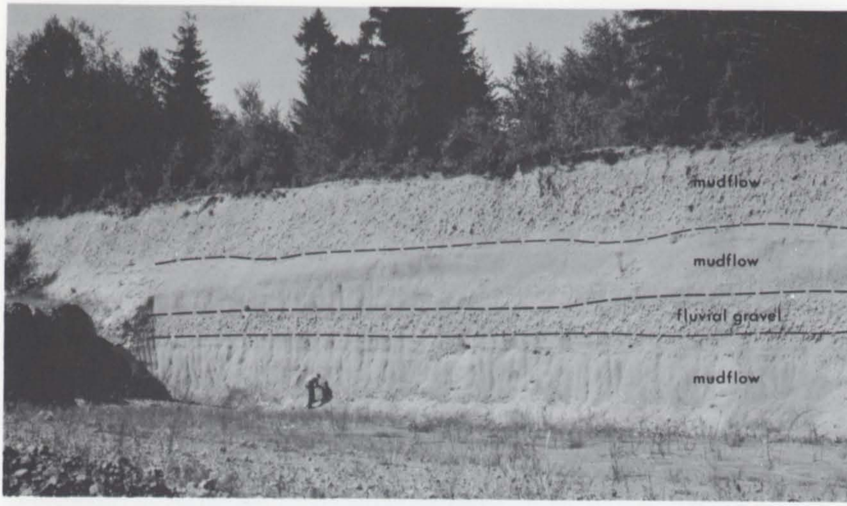


FIGURE 7.—Succession of three mudflow deposits and a fluvial gravel in the North Fork Toutle River valley about 45 km downvalley from Mount St. Helens. The deposits were formed during an eruptive period between 800 and 1200 B.C. and buried the valley floor to depths of 10-15 m.

eruptions; water may be provided by rain, melting snow, or the overflow of a crater lake. Mudflows can also be started by lava or a hot pyroclastic flow moving across snow, and can be either hot or cold, depending on the presence or absence of hot rock debris in the mudflow.

Mudflows can move considerable distances at high speed—some have been reported to travel at speeds of as much as 85 km/h. Velocity depends mostly on the fluidity of the flow and the slope on which it is moving; the size of the area affected depends mainly on the mudflow's volume. Swiftly moving mudflows rise along the outside of bends in their channels and slop up onto obstacles in their paths. Mudflows of very large volume may overtop streambanks and spread laterally if adjacent surfaces are of low relief.

The chief danger to human life is that of burial and impact of large boulders carried in mudflows. In addition, mudflows carrying hot rock debris could cause severe burns. Buildings and other structures can be buried, smashed, or removed. Because of their high viscosity and vast carrying power, mudflows can sweep away bridges as well as other massive and heavy structures in their paths. Natural or artificial constrictions in a valley that impede flowage, such as bridges and culverts, cause a mudflow to pond temporarily, deepen, and perhaps cover areas that would otherwise not be affected by the mudflow.

Mudflows from Mount St. Helens contain mostly newly erupted rock debris. These mudflows probably were caused by slides of such rock debris from the flanks of the volcano, or by rapid melting of deep snow by hot

pyroclastic flows. If a snowpack were to be melted by a pyroclastic flow, the resulting water could carry a large amount of rock debris derived from the flow itself. If the melting were caused by a lava flow or by a hot ash cloud, the melt water might not carry a large amount of rock debris initially, but torrents racing down slopes, gullies, and valley floors, and eroding loose deposits, would quickly become mudflows, and the total amount of material moving downvalley would thereby greatly increase.

The absence of an appreciable amount of clay in mudflows from Mount St. Helens suggests that large areas of hydrothermally altered rock did not exist on the volcano in the past, nor are they present today. For this reason, mudflows as large as the largest from Mount Rainier volcano (Crandell, 1971) are not likely to occur in the foreseeable future at Mount St. Helens. This conclusion is especially important in relation to the capacity of the reservoirs in the Lewis River valley. For example, the volume of one mudflow from Mount Rainier (at least 2 billion $m^3$ (Crandell, 1971, p. 26)) is probably more than twice as great as the volume of Swift Reservoir. The vast size of some mudflows from Mount Rainier is attributed to the sliding from the volcano of huge clayey masses of hydrothermally altered rock that probably were already saturated with water and steam at the time of sliding (Crandell, 1971, p. 17).

If a major eruption occurs, one of the greatest potential hazards involves Swift Reservoir. If a volcanic event led directly or indirectly to the failure or overtopping of Swift Dam, a catastrophe could result. A mudflow of very large volume, for example, could raise the level of the reservoir faster than water could be discharged safely. In addition, if such a flow entered the reservoir rapidly, it could create a wave that might overtop the dam if the lake level were high. The Pine Creek and Swift Creek valleys are the two routes by which a mudflow could enter the reservoir. Of these routes, Swift Creek is potentially the most dangerous because of its shorter access route from the volcano to the reservoir.

The largest single mudflow that might be expected to suddenly enter Swift Reservoir would probably have a volume of no more than 125 million $m^3$ (a volume equivalent to roughly 100,000 acre-feet). This estimate is based on the assumption that the worst foreseeable event would be the eruption of a hot pyroclastic flow similar in size to one that occurred between 2,500 and 3,000 years ago, which would spread over an area of about 30 $km^2$ south of the volcano. If an area of this size were to be covered with snow 5 m deep (assumed density of 0.25), all of which was melted by the pyroclastic flow, the water thus released would have a volume of 35-40 million $m^3$. This much water could mobilize about 75 million $m^3$ of rock debris to form a mudflow with an overall volume of at least 110 million $m^3$. This is equivalent to about 90,000 acre-feet.

The overall capacity of Swift Reservoir is about 920 million $m^3$ (756,000 acre-feet), of which about 545 million $m^3$ (446,000 acre-feet) is usable capacity. A lowering of the reservoir that would make available 125 million

$m^3$ (100,000 acre-feet) of storage capacity should provide reasonable assurance against overtopping and failure. An even lower reservoir would further reduce the possibility that a water wave would overtop the dam. Thus, if the volcano becomes active, consideration should be given to maintaining at least 100,000 acre-feet of storage capacity in order to accommodate a sudden volume increase related to a volcanic event. Additional storage capacity would be desirable as a safety margin, the volume of which could change from season to season according to the likelihood of very heavy precipitation and runoff that could result from a major storm.

#### FLOODS

The danger presented by floods caused by volcanism is similar to that of floods of other causes. Those related to volcanism probably will carry unusually large amounts of rock debris, and deposits of sand and gravel many meters thick may result at localities on valley floors where the carrying power of the river decreases for any reason. If a major eruption of Mount St. Helens occurred during a time when the volcano was blanketed by deep snow, and when floods were caused by meteorological conditions, the resulting floods could be higher than normal and could affect valley floors at least as far downstream as the Columbia River.

## HAZARD ZONES

Much of the area close to Mount St. Helens, as well as certain parts of a much broader region, will be affected to some extent by future eruptions of the volcano. Some of these eruptions will endanger human lives or property, or both. Some volcanic events cause little danger to life because they occur so slowly that warning can be given, and people in threatened areas can leave, but other events occur so quickly that escape is not possible. However, even slowly acting events can endanger land and fixed structures. The kinds of risk described here do not distinguish between life and property and are not based on the type of present or future use of land around the volcano. Instead, they are based on the likelihood that certain areas will be affected by future eruptions in certain predictable ways, severity, and frequency. Two kinds of potentially dangerous phenomena are discussed here: (1) those that move along the surface of the ground, such as lava flows and mudflows, here designated as flowage hazards; and (2) those that are transported through the air, such as tephra and gases, here referred to as tephra hazards.

#### FLOWAGE-HAZARD ZONES

The boundaries of flowage-hazard zones shown on plate 2 are based on the extent of lava flows, pyroclastic flows, mudflows, and floods that have affected those areas during the last 4,500 years. The 4,500-year interval was chosen because of the large number and variety of eruptions that occurred during that time. Areas within flowage-hazard zone 1, which includes the

volcano and areas close to it, have repeatedly been affected by lava flows, pyroclastic flows, mudflows, or floods, or by all of these phenomena. If the volcano continues to behave as it has in the recent past, any part of this zone could be affected by similar phenomena at some time in the future. The part of the zone that has been affected most frequently in the past is the volcano itself, where the occurrence of such phenomena has averaged at least one per century. In general, the degree of risk within the zone decreases gradationally away from the center of the volcano.

Future eruptions are possible from a vent on any side of the volcano, and the effects of some of the resulting volcanic phenomena could be confined to a single flank of the mountain.

Flowage-hazard zone 2 consists of areas that have been affected by mudflows and floods caused by volcanic activity during the last 4,500 years. The boundary between zones 1 and 2 is gradational, and future lava flows and pyroclastic flows may reach into some parts of zone 2 nearest the volcano. The degree of risk within zone 2 decreases gradationally both with distance downvalley and with height above present rivers. The inferred average frequency of mudflows in areas in zone 2 ranges from at least one in 500 years at the upvalley end of the zone to one in 3,000 years at the downvalley end.

Zone 3 includes valley-floor areas, beyond the known extent of mudflows, which have been affected by floods probably caused directly or indirectly by volcanism. Although water depths or the downvalley extent of future floods cannot be predicted, if floods caused by eruptions coincided with heavy rains or rapid snowmelt, rivers heading at the volcano could reach higher stages than would normally be expected from floods resulting solely from weather conditions.

## TEPHRA-HAZARD ZONES

The tephra-hazard zones (fig. 8) are based on records of wind directions and speeds, as well as extents of three tephra deposits. These deposits are an unnamed tephra formed in 1842; layer T, which was erupted about A.D. 1800; and layer Yn, which was formed about 4,000 years ago (about 3,400 radiocarbon years ago (Mullineaux and others, 1975)). These three deposits involved volumes on the order of 0.01, 0.1 and 1 $km^3$, respectively, and are representative of tephra eruptions of small, moderate, and large volumes from Mount St. Helens. Figure 9 shows how these three deposits decrease in thickness at very different rates downwind from the volcano. Future tephra eruptions may not be identical to those of the past, but past eruptions serve as illustrations of a range of likely future conditions. Eruptions of small volume probably will occur much more frequently than those of large volume. Judging from the record of the past, we can estimate that small eruptions will occur about once per 100 years, on the average. Eruptions of moderate volume may occur as often as about once per 500-1,000 years, and significantly larger eruptions may occur about once every 2,000-3,000 years.

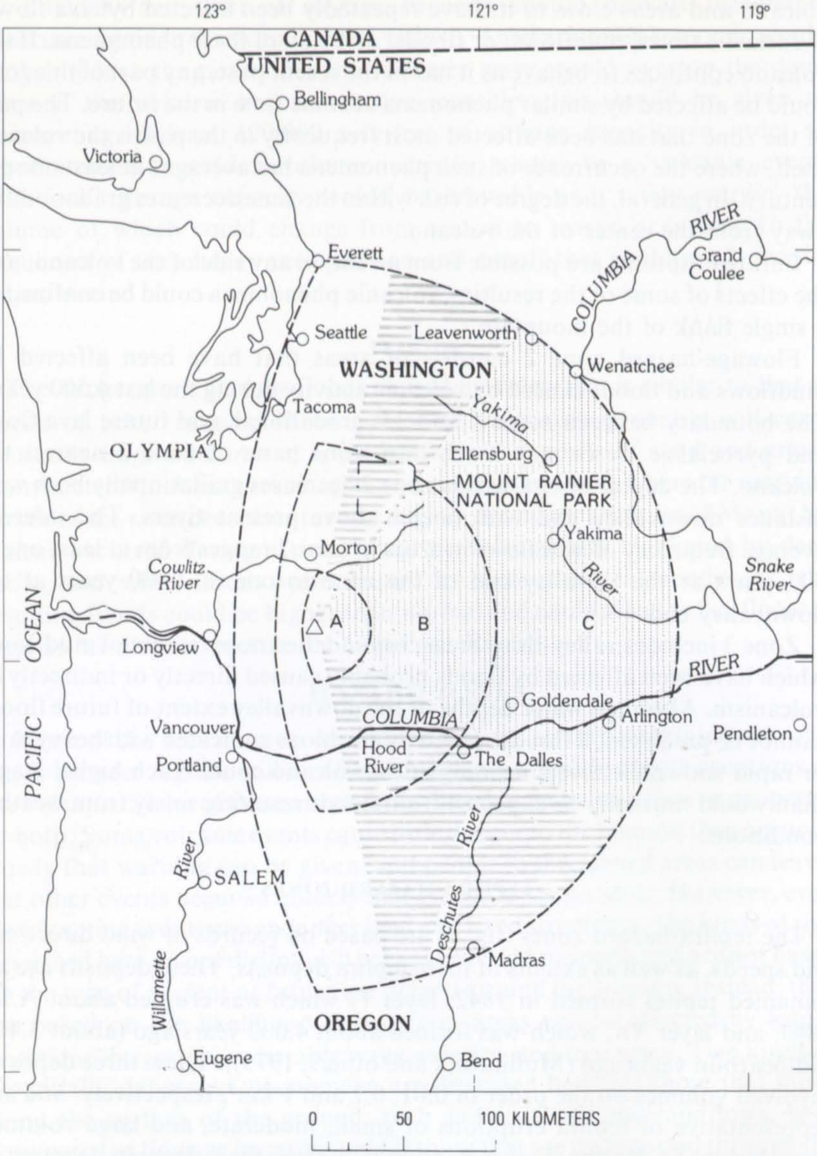


FIGURE 8.—Tephra-hazard zones (dashed outlines). Potential tephra thickness is greatest in zone A, and progressively less in zones B and C. (Compare fig. 9.) In each zone, potential thickness decreases outward from the volcano as distance increases. Winds blow from the volcano toward the sectors shown by horizontal and vertical lines about 80 percent of the time, and toward the vertically lined sector about 50 percent of the time. Thus, these sectors include the areas in which tephra will fall most frequently during future eruptions.

The previously discussed severity of the effects of tephra is determined chiefly by the amount that falls at a given place, although the size of the

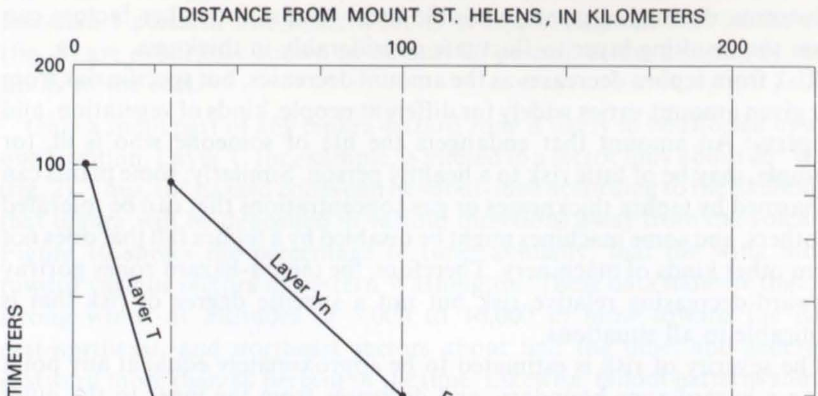


FIGURE 9.—Relation between distance downwind from the volcano and estimated average present thickness of tephra along the thickest parts of lobes. The tephra layers may have been as much as twice as thick as shown here when they were deposited. The lines represent three tephra deposits of different volumes: layer Yn, layer T, and an unnamed layer formed in 1842. These are estimated to have volumes, respectively, on the order of 1 $km^3$, 0.1 $km^3$, and 0.01 $km^3$. The expectable frequencies of similar eruptions in the future are based on the eruptive behavior of Mount St. Helens during the last 4,500 years.

particles, rate of accumulation, and amounts and kinds of associated gases can also be significant. In general, the volume of material erupted determines thickness—large volumes result in thick deposits. Tephra deposits could be laid down within a broad arc close around the volcano if winds are weak and variable. If winds are strong and uniform, the same volume of material would form thicker deposits along a narrow band leading away from the volcano. If the material erupted is fine grained, or if winds at levels reached by the material are strong and uniform in direction, thick deposits could reach relatively far from the volcano. Ideally, a tephra deposit would thin

gradually and regularly with increasing distance from its source. However, rainstorms during transport, variable local winds, and other factors can cause the resulting layer to fluctuate considerably in thickness.

Risk from tephra decreases as the amount decreases, but specific risk from any given amount varies widely for different people, kinds of vegetation, and property. An amount that endangers the life of someone who is ill, for example, may be of little risk to a healthy person. Similarly, some plants can be harmed by tephra thicknesses or gas concentrations that can be tolerated by others, and some machines might be disabled by a tephra fall that does not harm other kinds of machinery. Therefore, the tephra-hazard zones portray outward-decreasing relative risk but not a specific degree of risk that is applicable to all situations.

The severity of risk is estimated to be approximately equal at any point along a hazard-zone boundary, and decreases from the inner to the outer boundary within each zone. East of Mount St. Helens, the boundaries of zones in figure 8 have been placed at 30, 100, and 200 km, because thicknesses of the tephra deposits on which the subdivisions are based are relatively well known at those distances. These thicknesses may not have any special significance with respect to potential effects.

Wind-speed data as well as tephra of previous eruptions indicate that areas of potential hazard are less extensive west of the volcano than toward the east. Average and maximum wind speeds toward the west-northwest and west are generally less than half of those toward the east and northeast, and wind speeds are lower toward all westerly points of the compass (table 3).

TABLE 3.—*Mean wind speeds, in knots, at various altitudes*

[Approximate altitude in meters. Based on 20-year record (1950-70) at Quillayute, Wash. One knot=1.15 m/h or 1.85 mi/h; Winds Aloft Summary of the Air Weather Service, U.S. Air Force, available from the National Climatic Center, Asheville, N.C.]

| From | N. | NNE. | NE. | ENE. | E. | ESE. | SE. | SSE. | S. | SSW. | SW. | WSW. | W. | WNW. | NW. | NNW. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Toward | S. | SSW. | SW. | WSW. | W. | WNW. | NW. | NNW. | N. | NNE. | NE. | ENE. | E. | ESE. | SE. | SSE. |
| *Altitude:* | | | | | | | | | | | | | | | | |
| 3,000 | 18.6 | 16.3 | 14.8 | 11.5 | 11.6 | 12.4 | 13.8 | 18.1 | 24.2 | 25.7 | 25.4 | 24.2 | 23.5 | 21.8 | 22.4 | 21.2 |
| 4,300 | 26.7 | 21.7 | 18.7 | 15.1 | 13.7 | 15.5 | 18.2 | 21.5 | 27.2 | 30.7 | 31.3 | 31.1 | 31.0 | 29.4 | 29.6 | 28.5 |
| 5,500 | 33.2 | 27.8 | 27.9 | 18.5 | 17.6 | 16.8 | 20.8 | 22.9 | 32.2 | 36.6 | 38.6 | 38.3 | 38.4 | 37.3 | 35.7 | 36.9 |
| 9,100 | 48.6 | 43.8 | 36.5 | 29.9 | 30.2 | 26.4 | 32.2 | 38.0 | 46.8 | 52.5 | 55.9 | 55.4 | 56.2 | 50.8 | 51.6 | 53.9 |
| 12,200 | 40.9 | 31.5 | 30.3 | 14.9 | 19.7 | 16.9 | 18.8 | 28.0 | 35.8 | 43.8 | 48.5 | 50.3 | 50.9 | 46.2 | 46.3 | 45.4 |
| 16,200 | 20.1 | 12.4 | 11.3 | 6.3 | 6.4 | 9.0 | 9.7 | 13.8 | 15.5 | 21.1 | 23.7 | 25.8 | 26.2 | 25.1 | 23.7 | 21.4 |
| Average | 31.4 | 25.6 | 23.2 | 16.0 | 16.5 | 16.1 | 18.9 | 23.7 | 30.3 | 35.1 | 37.2 | 37.5 | 37.7 | 35.1 | 34.9 | 34.6 |

The few tephra deposits that are known to extend west of the volcano reach less than 10 percent as far as similar beds extend toward the east. Strong winds blowing into a 22.5° sector toward the west at all altitudes likely to be reached by tephra evidently are so rare that they have never coincided with an eruption of Mount St. Helens. A review of wind records from Salem, Oreg., and Quillayute, Wash., the two closest stations for which such records

are available, suggests that the likelihood of such a combination of winds is less than 1 percent. The western limits of tephra-hazard zones on the map (fig. 8) are arbitrarily shown to be only 25 percent of the distance of those limits to the east.

Only a small part of any tephra-hazard zone is likely to be affected by any one eruption. Layer T, for example, is limited to a sector only about 25° wide (fig. 2). Thus, the hazard zones can be subdivided according to the likelihood that tephra will be deposited in various directions away from the volcano. Figure 10 shows the percentage of time, annually, that the wind blows toward various sectors in western Washington. These data indicate that the strong winds at altitudes of 3,000 to 16,000 m blow toward the east, east-northeast, and northeast sectors about half the time, and generally eastward more than 80 percent of the time. Likewise, fallout patterns show a

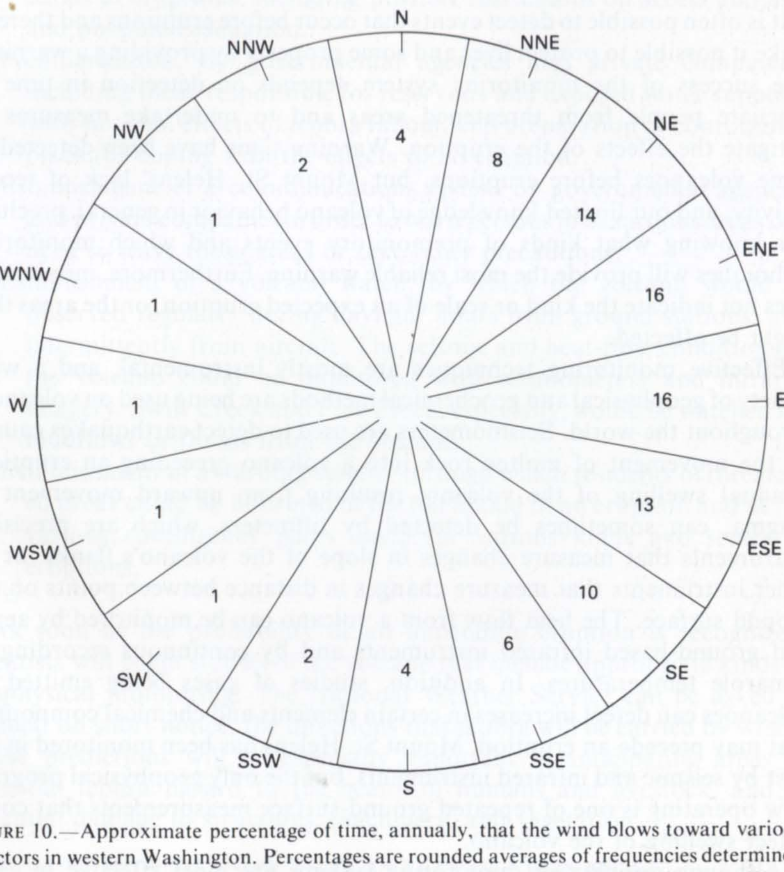


FIGURE 10.—Approximate percentage of time, annually, that the wind blows toward various sectors in western Washington. Percentages are rounded averages of frequencies determined at various altitudes between 3,000 and 16,000 m at Salem, Oreg., and Quillayute, Wash. (Winds Aloft Summary of the Air Weather Service, U.S. Air Force, available from the National Climatic Center, Asheville, N.C.).

strong preferred orientation toward the east and northeast. The five largest tephra deposits of the last 4,500 years, for example, trend in those directions (fig. 2), and more than 90 percent of the known tephra deposits of all ages from Mount St. Helens lies east of the volcano.

## FUTURE ERUPTIONS AND MITIGATION OF THEIR EFFECTS

Future eruptions of Mount St. Helens are a near certainty. It will not be possible to prevent them, or to stop them after they have begun. It is generally not feasible to divert or control the eruptive products from a volcano like Mount St. Helens. However, loss of lives and loss or damage to property can be lessened by establishing procedures to be followed if an eruption should occur, and by monitoring the volcano to detect an approaching eruption.

### MONITORING

It is often possible to detect events that occur before eruptions and thereby make it possible to protect lives and some property by providing a warning. The success of the monitoring system depends on detection in time to evacuate people from threatened areas and to undertake measures to mitigate the effects of the eruption. Warning signs have been detected at some volcanoes before eruptions, but Mount St. Helens' lack of recent activity, and our limited knowledge of volcano behavior in general, preclude our knowing what kinds of premonitory events and which monitoring techniques will provide the most reliable warning. Furthermore, monitoring does not indicate the kind or scale of an expected eruption, or the areas that might be affected.

Effective monitoring techniques are mostly instrumental, and a wide variety of geophysical and geochemical methods are being used on volcanoes throughout the world. Seismometers are used to detect earthquakes caused by the movement of molten rock into a volcano preceding an eruption. Gradual swelling of the volcano, resulting from upward movement of magma, can sometimes be detected by tiltmeters, which are precision instruments that measure changes in slope of the volcano's flanks, or by other instruments that measure changes in distance between points on the ground surface. The heat flow from a volcano can be monitored by aerial and ground-based infrared instruments and by continuous recording of fumarole temperatures. In addition, studies of gases being emitted by volcanoes can detect increases in certain elements and chemical compounds that may precede an eruption. Mount St. Helens has been monitored in the past by seismic and infrared instruments, but the only geophysical program now operating is one of repeated ground-surface measurements that could detect swelling of the volcano.

Although geophysical monitoring systems are most effective in early detection of an impending eruption, people near a volcano often notice premonitory events well before an eruption actually begins. Both the magnitude and frequency of earthquakes, for example, generally increase as

an eruption approaches, and earthquakes often become strong enough to be felt by people. Some of the earthquakes may trigger avalanches of snow or rock from the volcano. Such avalanches may also be caused by tilting of the ground surface which results from swelling of the volcano as magma moves into it. In addition, increased heat within the volcano commonly produces clouds of water vapor and unusually rapid melting of snow in localized areas.

### WHAT TO DO WHEN WARNING SIGNS OF AN ERUPTION OCCUR

If there are signs of an approaching eruption, actions that could reduce its possible effects on people and property include:

1. Notification of County, State, and Federal authorities.
2. Preparation of contingency plans by governmental agencies and private companies responsible for management of areas adjacent to and downvalley from the volcano for responding to various kinds and scales of eruptions, including possible restrictions on access and use, and possible evacuation.
3. Familiarization, by governmental agencies and private companies, including those responsible for reservoirs and exposed water supplies, with possible effects of tephra fallout, and preparation of contingency plans for coping with the effects of an eruption.
4. Establishment of a communications system by governmental agencies and private companies in order to warn persons in hazardous areas of a need to leave those areas or take other precautions.
5. Establishment of a volcano watch, by which the volcano would be observed regularly during daylight hours from ground stations, and intermittently from aircraft. The seismic and heat-flow conditions of the volcano could be monitored with seismometers and infrared imagery. Swift Creek and Pine Creek, especially, would be watched for mudflows or floods from the volcano.
6. Establishment of a warning system, through which residents of threatened areas could be informed of the likelihood of an eruption and of the various contingency plans made for various kinds and scales of eruptions.

As soon as the probability of an impending eruption is recognized, scientists will begin studies of the volcano that include appropriate kinds of geophysical monitoring. The National Weather Service can be asked to predict, on short notice, the directions that tephra will be carried by winds. These predictions will be especially important in anticipating areas of potential tephra hazard to the health of humans and livestock, and of potential damage to structures, machinery, and vegetation.

### HOW TO KNOW THAT AN ERUPTION HAS BEGUN

Volcanic eruptions can begin in a variety of ways. Initial activity on a small scale might not be detected if weather conditions were to cause poor visibility. At Lassen Peak, Calif., the initial eruptions in 1914 of volcanic

activity that was to continue for 3 years were relatively mild emissions of tephra and steam. A violent eruption did not occur until 1915. In contrast, other andesitic and dacitic volcanoes have been known to erupt violently with little or no small-scale preliminary activity.

If an eruption begins on a relatively small scale, it will probably first be recognized by one or more of the following events:

Clouds of white to gray steam and tephra or "smoke" rising above volcano.

Glow in sky above volcano at night.

Darkening, by tephra, of snow on volcano's flanks.

Loud rumbling noises or sharp explosions.

Appearance of floating pumice in streams that drain the volcano.

During an eruption of Mount St. Helens in 1853, clouds of tephra and steam rising above the volcano were seen from a point 150 km to the west, and also from Salem, Oreg., 155 km to the south-southwest. Explosions accompanying an eruption in 1848 were heard 100 km south-southwest of the volcano, at Oregon City, Oreg. (Harris, 1976, p. 185). These observations suggest to us that the next eruption might be heard over a broad area and may be seen from much of western Washington and northwestern Oregon.

## WHAT TO DO WHEN AN ERUPTION BEGINS

If an eruption begins, prompt action by individuals and governing agencies may save lives as well as property. Immediate actions to be undertaken include:

1. Notification of local, State, and Federal authorities.
2. Activation of contingency plans.
3. Preparation by persons on and near the volcano, and on valley floors close to the volcano, to leave on short notice and to stay away until the risk has been evaluated by responsible authorities.
4. Consideration of lowering the level of Swift Reservoir. If the eruption occurs at the summit or on the south flank of the volcano, the reservoir could, if deemed advisable, be kept at a level that would accommodate the largest mudflow that could reasonably be expected to move into it without causing overtopping or failure.

## PREDICTING THE NEXT ERUPTION

The present dormant state of Mount St. Helens began in 1856, and no way is now known of determining when the volcano will erupt again. Mount St. Helens' behavior pattern during the last 4,500 years has been one of spasmodic periods of activity, separated by five or six dormant intervals of a little more than 2 to about 5 centuries' duration. In addition, 12 dormant periods 1 or 2 centuries in length have been identified, and many intervals of a few years or a few decades surely occurred during prolonged periods of

intermittent eruptive activity. The volcano's behavior pattern suggests that the current quiet interval will not last as long as a thousand years; instead, an eruption is more likely to occur within the next hundred years, and perhaps even before the end of this century.

It has been suggested that all three rock types erupted at Mount St. Helens in the past have been derived from an andesitic parent magma, and that a typical eruptive period starts with the appearance of an explosive gas-rich dacite which forms pumice (Hopson, 1971). This is followed successively by the formation of a dacite dome and lava flows of andesite and possibly basalt. Hopson implied that such a succession would occur over a period of a few years or several decades. If such a sequence is followed during future eruptions, the greatest potential danger will exist at or soon after the onset of volcanic activity. However, not all past eruptions at Mount St. Helens have followed this idealized succession, and it is by no means certain that all future eruptions will.

It is quite possible that any of the three rock types will be erupted singly or in some combination in the future. One possible sequence could start with the eruption of a small amount of an andesite or basalt tephra from a vent on the volcano's flank, followed by a lava flow of similar composition from the same vent. Or it is conceivable that dacite tephra could be erupted from one vent as andesite or basalt tephra and lava flows were being erupted at another vent if magmas of different composition were present beneath the volcano at the same time.

Because of the variable behavior of the volcano, we cannot be sure whether the next eruption will produce lava flows, pyroclastic flows, tephra, or volcanic domes, or some combination of these. If the next eruptive period is like the last, which continued from about 1831 to 1856, intermittent activity on various scales and of various kinds can be expected over a period of several decades.

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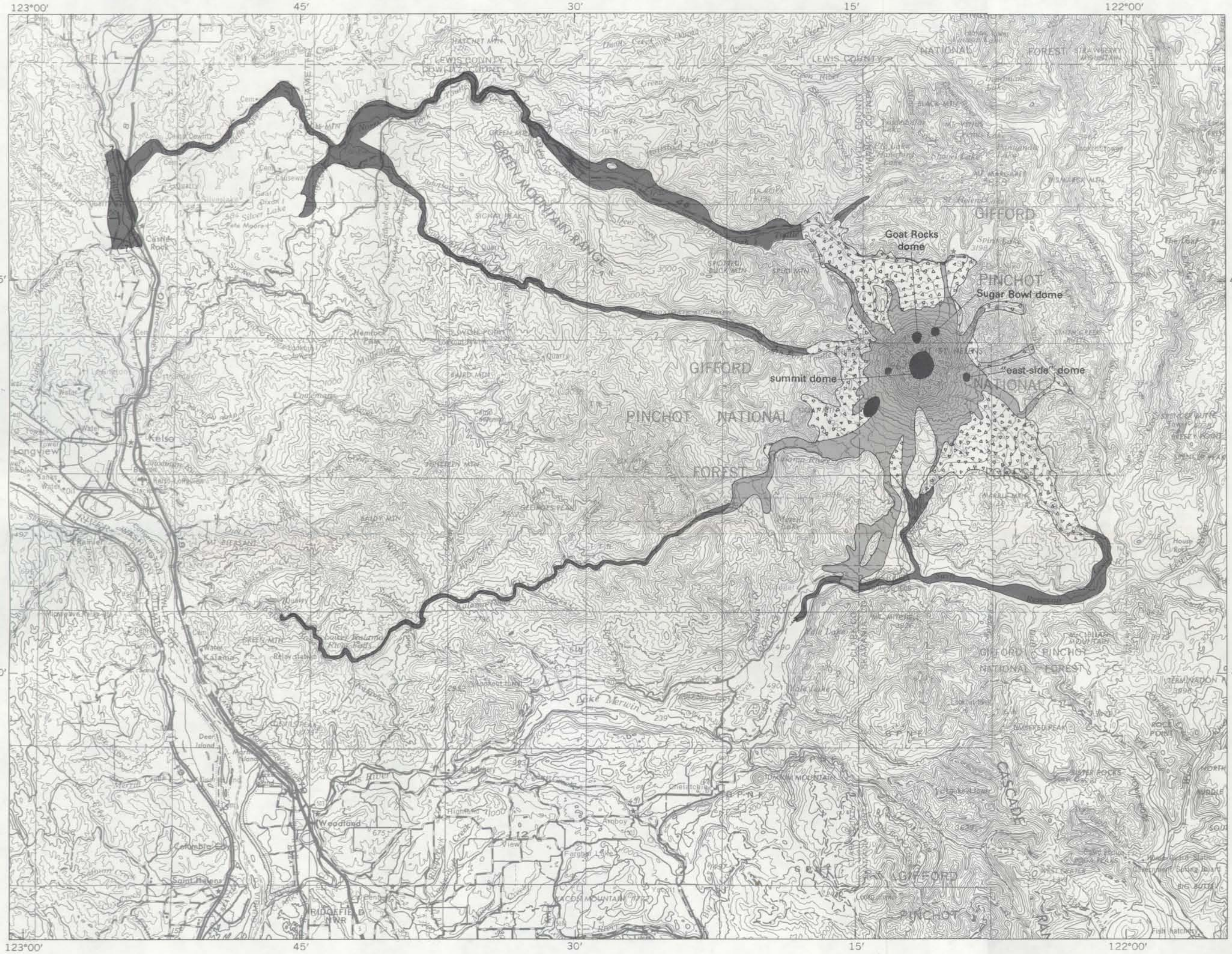
☆ U.S. GOVERNMENT PRINTING OFFICE: 1980—777-034/16

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

Crandell and Mullineaux—POTENTIAL HAZARDS FROM FUTURE ERUPTIONS, MOUNT ST. HELENS VOLCANO, WASH.—Geological Survey Bulletin 1383–C

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

BULLETIN 1383-C
PLATE 1




Base from U.S. Geological Survey
Yakima, 1958; The Dalles, 1953;
Vancouver, 1958; Hoquiam, 1958

SCALE 1:250 000

5 0 5 10 15 MILES

5 0 5 10 15 KILOMETERS

CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Based chiefly on reconnaissance geologic mapping by D. R. Crandell; extents of domes are based on geologic mapping by C. A. Hopson (written commun., 1974)

# VOLCANIC ROCKS AND UNCONSOLIDATED DEPOSITS FORMED AT MOUNT ST. HELENS DURING THE LAST 4,500 YEARS

## EXPLANATION

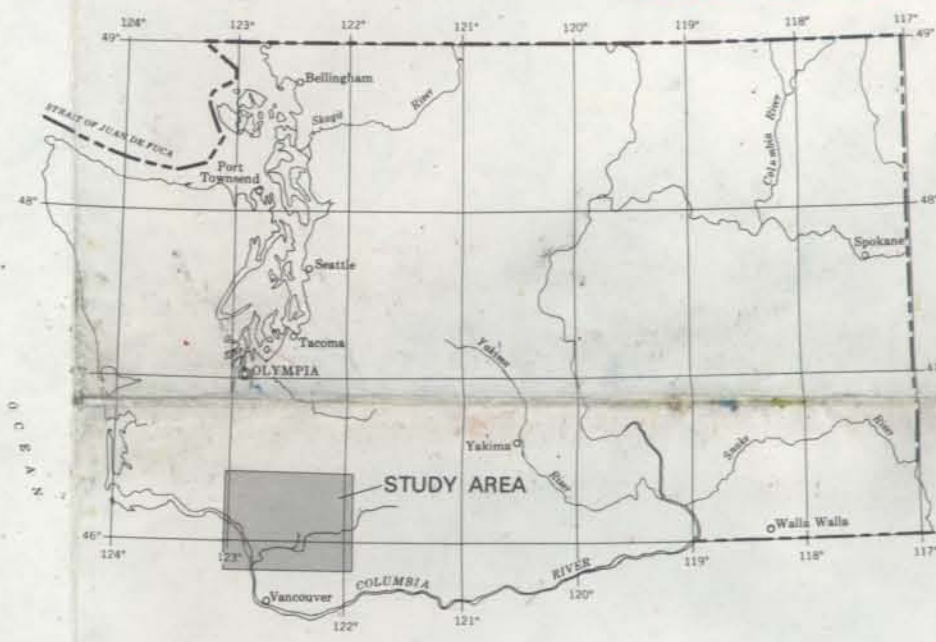
DOMES—Includes short, thick lava flows

LAVA FLOWS—Locally overlain and underlain by pyroclastic-flow deposits and mudflows

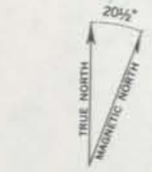
PYROCLASTIC-FLOW DEPOSITS—Locally includes mudflows

MUDFLOWS—Locally includes fluvial deposits, outline queried where limits are unknown






INDEX MAP OF WASHINGTON




APPROXIMATE MEAN DECLINATION, 1978



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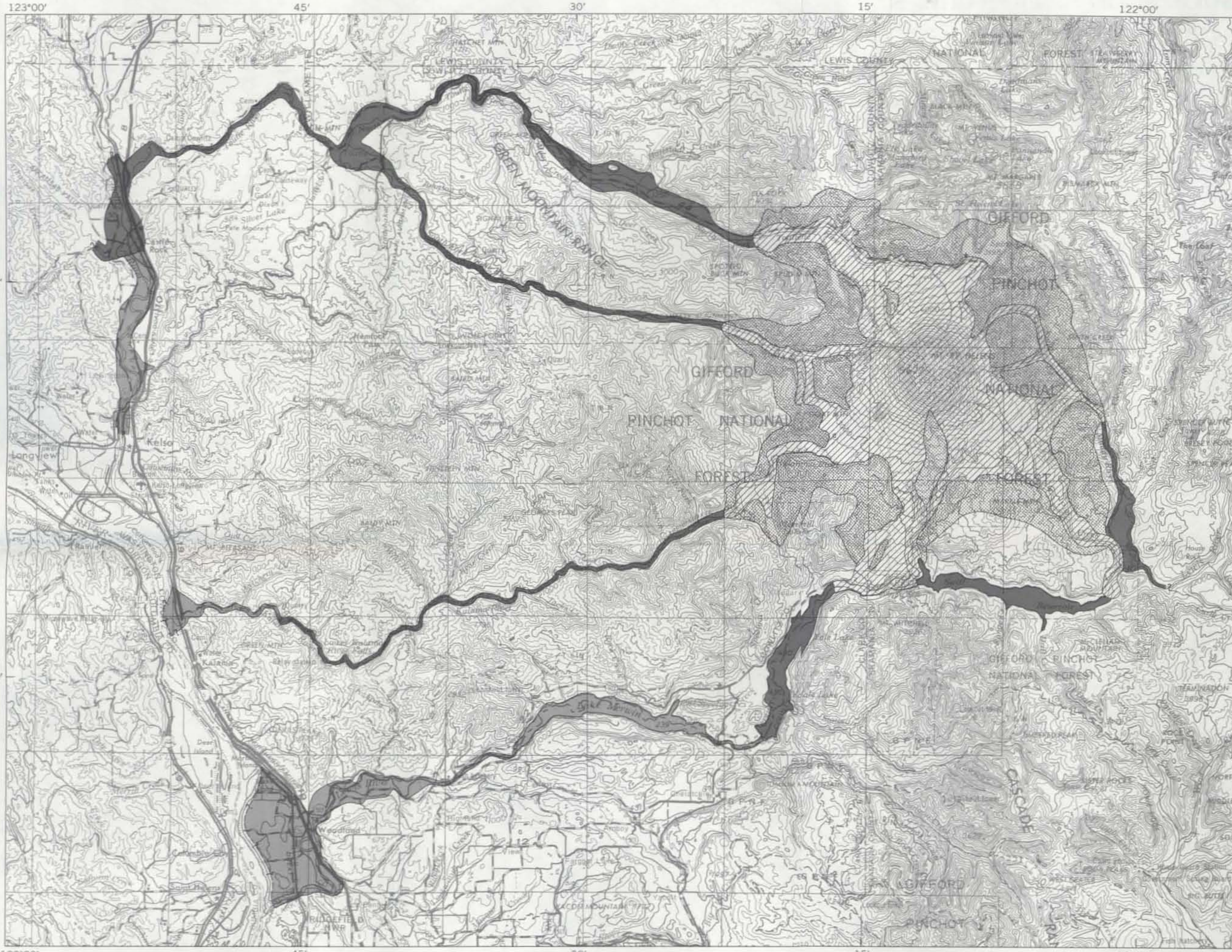
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

BULLETIN 1383-C
PLATE 2




Base from U.S. Geological Survey
Yakima, 1958; The Dalles, 1953;
Vancouver, 1958; Hoquiam, 1958

SCALE 1:250 000

5 0 5 10 15 MILES

5 0 5 10 15 KILOMETERS

CONTOUR INTERVAL 200 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

# AREAS OF POTENTIAL HAZARD FROM LAVA FLOWS, PYROCLASTIC FLOWS, MUDFLOWS, AND FLOODS THAT MAY RESULT FROM FUTURE ERUPTIONS OF MOUNT ST. HELENS

## EXPLANATION

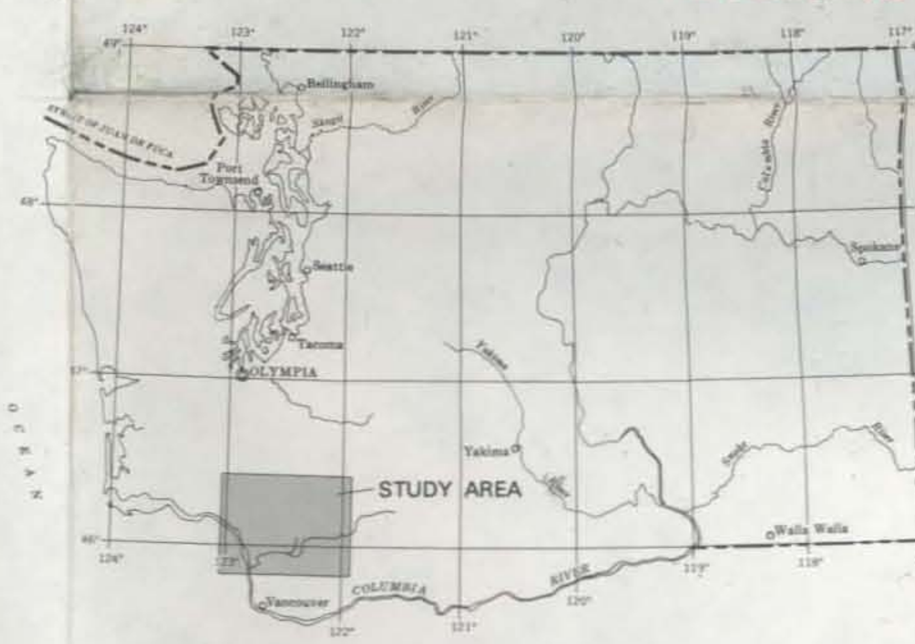
### FLOWAGE-HAZARD ZONES

FLOWAGE-HAZARD ZONE 1—Areas which could be affected by lava flows, pyroclastic flows, mudflows, and floods (line pattern), and ash clouds associated with pyroclastic flows (dot pattern)

FLOWAGE-HAZARD ZONE 2—Areas which probably could be affected only by mudflows and floods; includes Yale Lake and Swift Reservoir, which could be affected by large destructive waves if mudflows or pyroclastic flows moved into them; outline queried where extent unknown

FLOWAGE-HAZARD ZONE 3—Areas which probably could be affected only by floods; includes Lake Merwin, the level of which could be raised rapidly if water in reservoirs upstream were displaced by mudflows, pyroclastic flows, or floods; outline dashed and queried where extent unknown






INDEX MAP OF WASHINGTON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